MOND as an alternative to a dark universe

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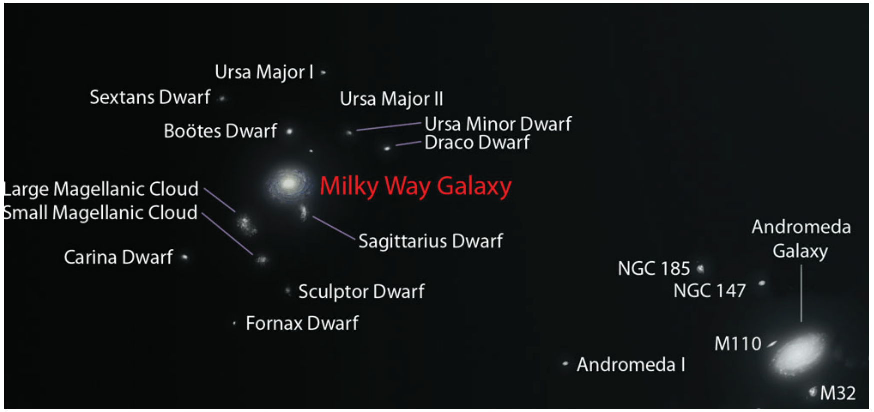
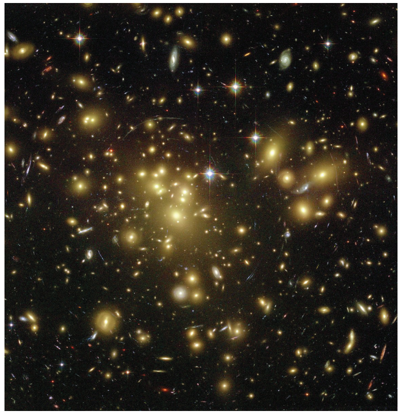
The mass-discrepancy problem

- Galactic systems held together by gravity balancing inertial forces
- Measure accelerations: $a \approx V^2/R$
- Assume Newtonian dynamics: $g \approx \frac{MG}{R^2}$, $a = g$
- Put together: $M \approx \frac{V^2 R}{G}$

The anomalies appear in

Equilibrium dynamics: Disc galaxies elliptical galaxies dwarf satellites, galaxy groups, clusters





Lensing

Universe at large from evolotion and structure formation.

We measure:

- Rotational speeds as function of radius in disc galaxies
- Velocity dispersions in ‘pressure-supported systems’ (dwarf spheroidals, elliptical galaxies, galaxy clusters)
- Temperatures and density profiles in of hot, pressure-supported gas (in elliptical galaxies and galaxy clusters)
- Bending of light or distortions of images due to gravitational lensing

We also measure the mass in baryons:

- Stars: convert light to mass
- Cold gas: 21 cm line emission is proportional to neutral Hydrogen mass (then add Helium in known proportion)
- Hot gas: x-ray emission.
- In the Universe most of the (nucleosynthesis) baryons are missing.

Dark matter?

- Evidence for gravitational anomalies, not directly for DM.
- No known form of matter (in the SM) can be the DM.
- Many experiments have failed to detect DM directly and indirectly.
- Another fix to standard dynamics is required – ‘dark energy’.
- Many observations conflicts with natural predictions of DM.
- Unexplained ‘coincidences’: $\rho(DM) \approx 5\rho(bar) \sim \rho(DE)$.
- Galactic systems had a haphazard, cataclysmic, and unknowable history in which baryons and DM act very differently.
- Galactic systems have baryon-to-DM ratios much smaller than the cosmic value.

MOND – synopsis

- MOND hinges on accelerations, noting that these are many orders of magnitude in galactic systems and the universe at large compared with lab and SS ones.

- Departure at small accelerations.

- Works very well in predicting the dynamics of many galaxies.

- Leaves some discrepancy in cluster. Not yet a coherent picture for cosmology.

- Strongly connected with cosmology in different ways.

- Several working self consistent theories (nonrelativistic and relativistic), but none the final MOND theory.

- MOND is a paradigm still under construction: an “effective” theory.

MOND – basic tenets

A theory of dynamics (gravity/inertia) involving a new constant a_0 (beside G, ...)

Standard limit ($a_0 \to 0$): The Newtonian limit

MOND limit : $a_0 \to \infty, \;\; G \to 0, \;\; Ga_0 \; fixed$:

Scale invariance: $(t, \mathbf{r}) \to \lambda(t, \mathbf{r})$

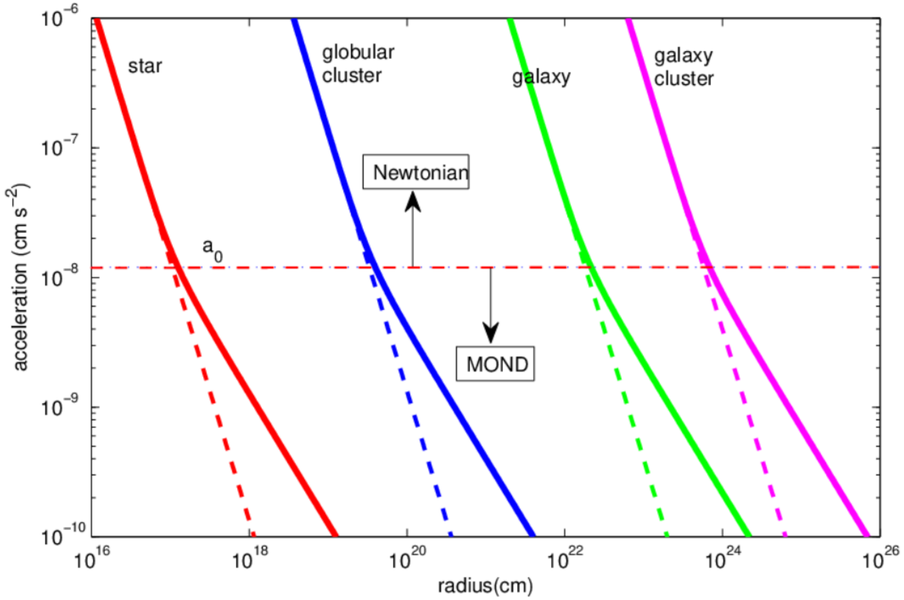
a_0 is analog to c in relativity or $\hbar$ in QM

Modified gravity or/and modified inertia (special relativity as MI).

Point-like central mass:

$$a = \frac{MG}{R^2} f\left(\frac{MG}{R^2 a_0}\right)$$

$$a \approx \begin{cases} MG/R^2 & : \quad a \gg a_0 \\ (MGa_0)^{1/2}/R & : \quad a \ll a_0 \end{cases}$$



Some Kepler-like MOND laws of galactic dynamics

- Asymptotic constancy of orbital velocity: $V(r) \to V_\infty$ (H)
- Light-bending angle becomes asymptotically constant (H)
- The velocity mass relation: $V_\infty^4 = MGa_0$ (H-B)
- Virial relation for systems with $a \ll a_0$: $\sigma^4 \sim MGa_0$
- Discrepancy appears always at $V^2/R = a_0$ (H-B)
- The central surface density of "dark halos" is $\approx a_0/2\pi G$ (H)
- Universal baryonic-dynamical central surface densities relation (H-B).
- Full rotation curves from baryon distribution alone (H-B)

These laws

- Essentially follow from only the basic tenets of MOND

- Are independent as phenomenological laws–e.g., if interpreted as effects of DM (just as the BB spectrum, the photo electric effect, H spectrum, superconductivity, etc. are independent in QM)

- Pertain separately to properties of the “DM” alone (e.g., asymptotic flatness, “universal” Σ), of the baryons alone (e.g., $M-\sigma$, maximum Σ), relations between the two (e.g., $M-V$)

- Revolve around a_0 in different roles

$a_0 = ?$

a_0 can be derived in several independent ways:

$$a_0 \approx 1.2 \times 10^{-8} \text{ cm s}^{-2}$$

$$\bar{a}_0 \equiv 2\pi a_0 \approx cH_0 \qquad\qquad \bar{a}_0 \approx c(\Lambda/3)^{1/2}$$

$$\ell_M \equiv c^2/a_0 \approx \ell_U$$

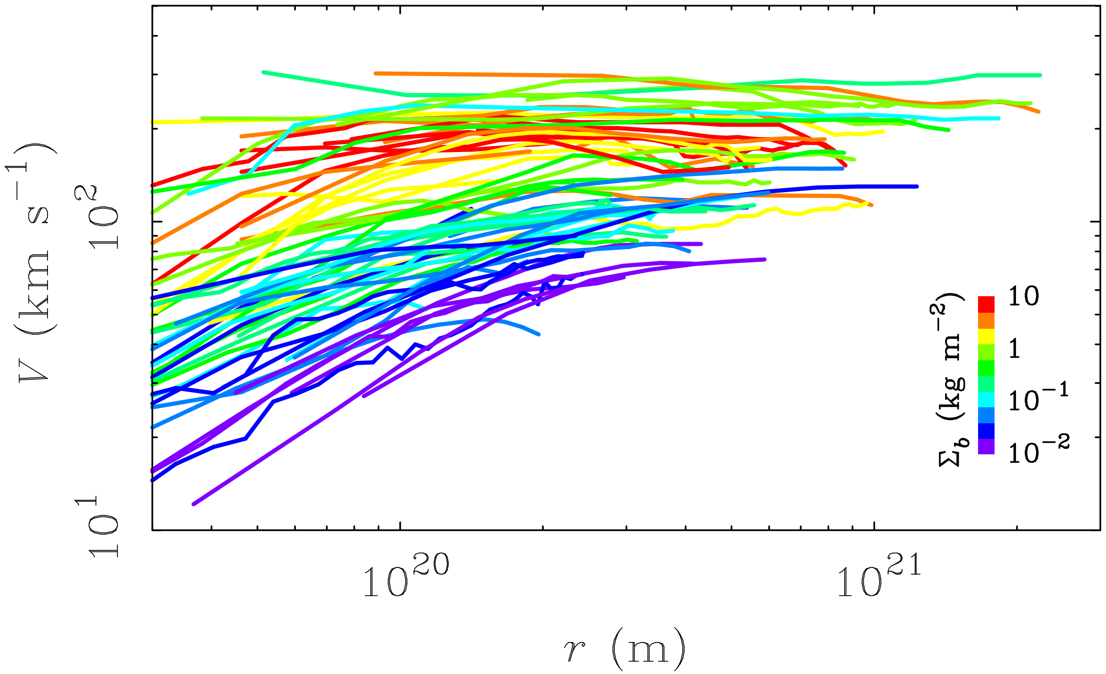
$$a \lesseqgtr a_0 \qquad \Leftrightarrow \qquad \ell_a \lesseqgtr \ell_U$$

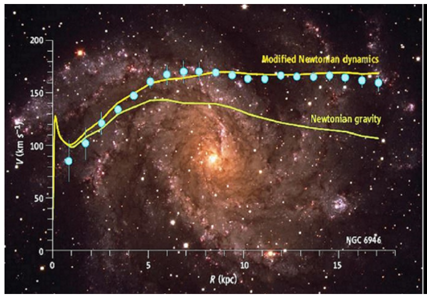
$$M_M \equiv c^4/Ga_0 \approx M_U$$

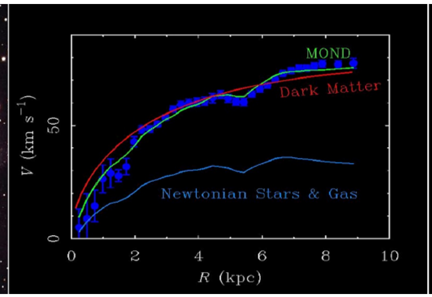
No deep-MOND black holes

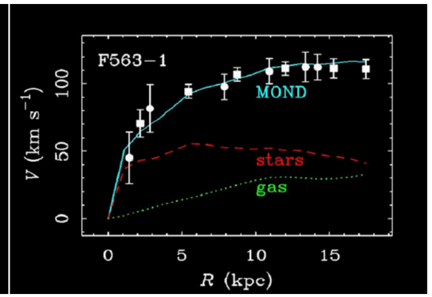
Asymptotic constancy of orbital velocity:

$$V(r) \to V_\infty$$

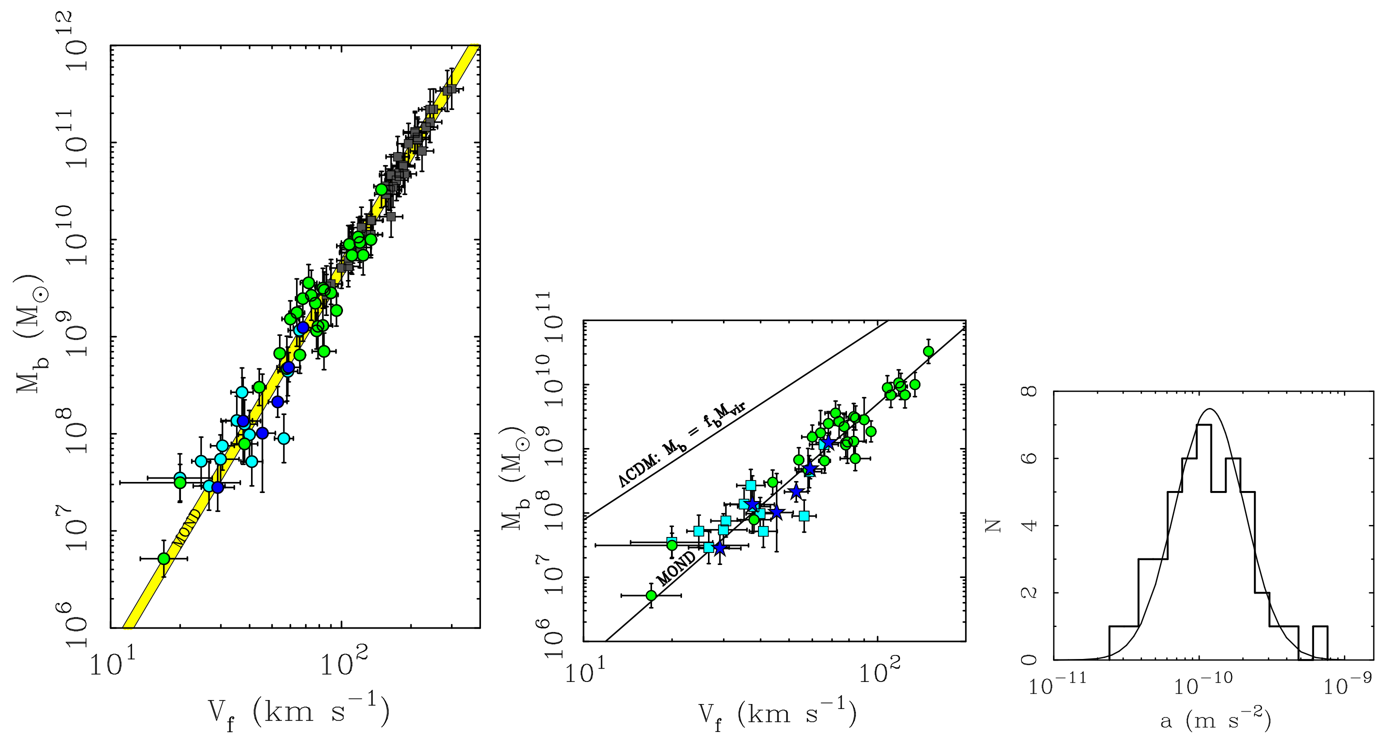








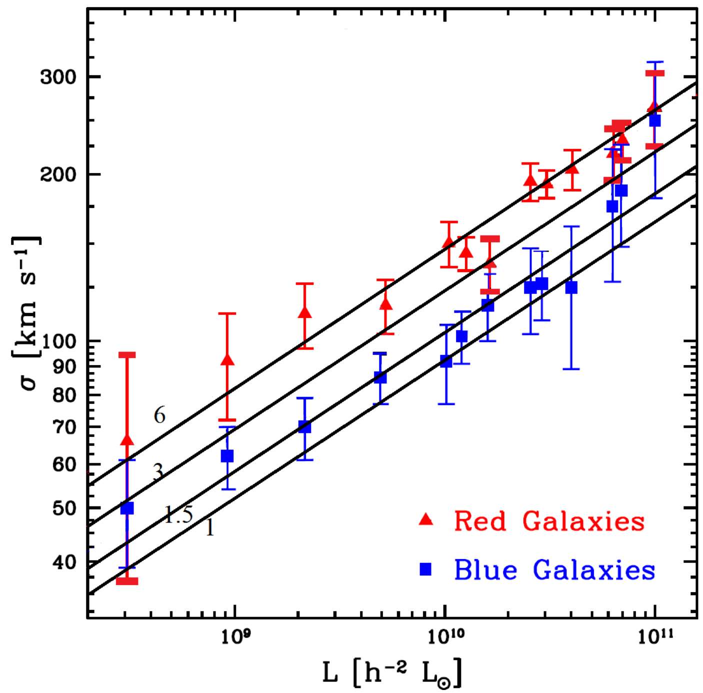
Asymptotic-velocity-mass relation: $V_\infty^4 = MGa_0$



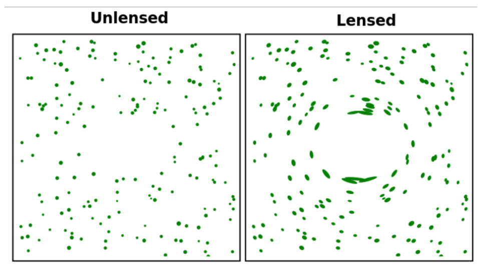
McGaugh (2011)

Scale invariance→ V_∞ depends only on M. Power 4 from acceleration. Intersect=Ga_0.

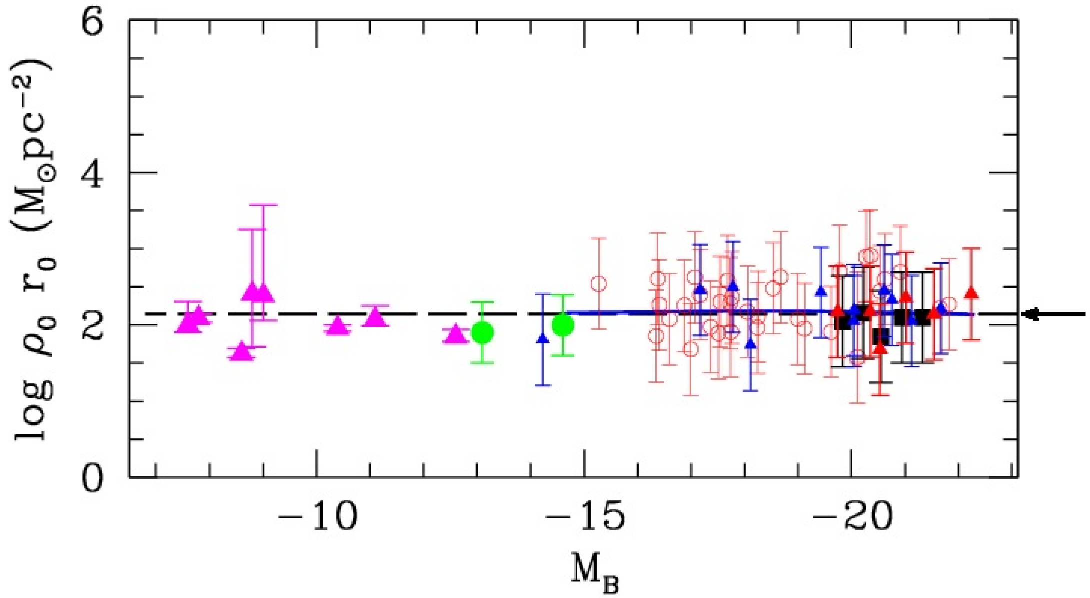
Asymptotic-velocity-mass relation from Galaxy-galaxy lensing



Brimioulle et al. 2013.



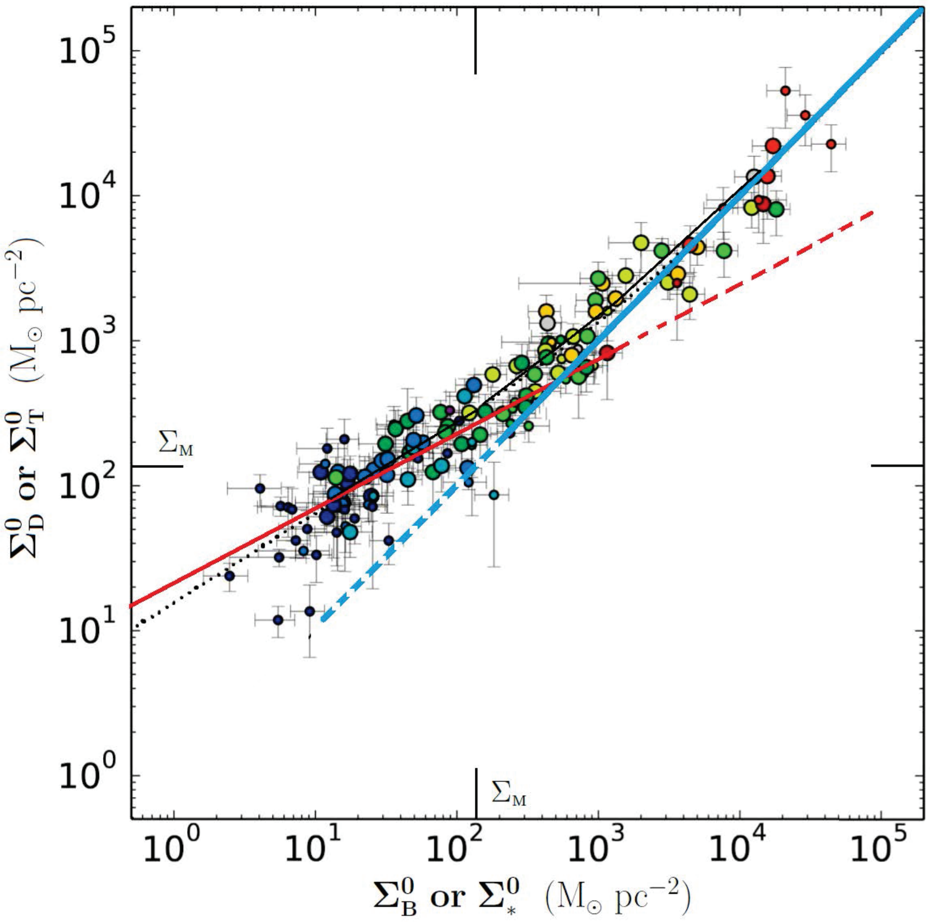
Central surface density of "dark halos" is $\approx a_0/2\pi G$



Salucci et al. 2012

$log(a_0/2\pi G) = 2.14$ (in the units in the figure)

Universal baryonic-dynamical central surface densities relation



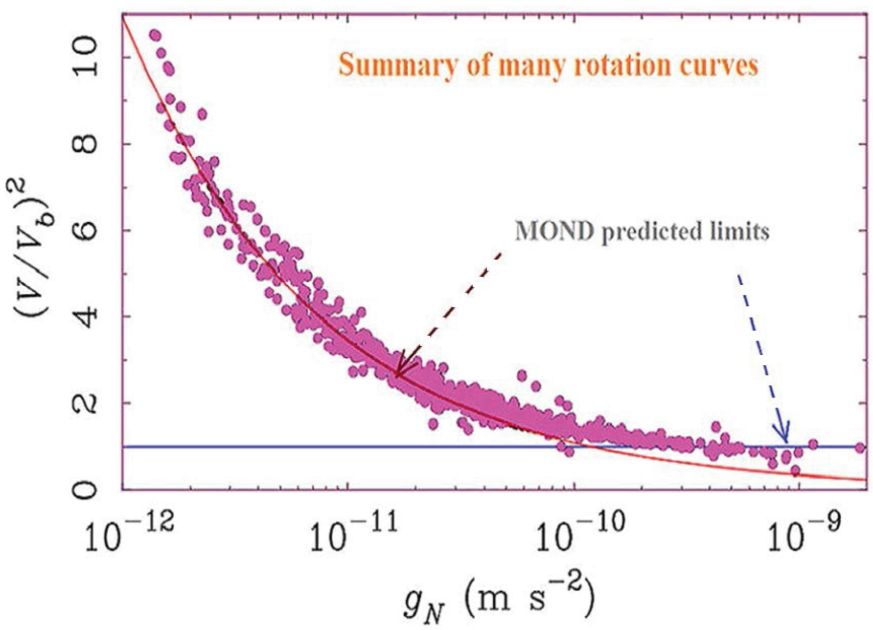
Data: Lelli et al. 2016. 'Scatter largely driven by obs. uncertainties'. 'virtually no intrinsic scatter'.

Discrepancy-acceleration correlation

Discrepancy appears always at $V^2/R = a_0$

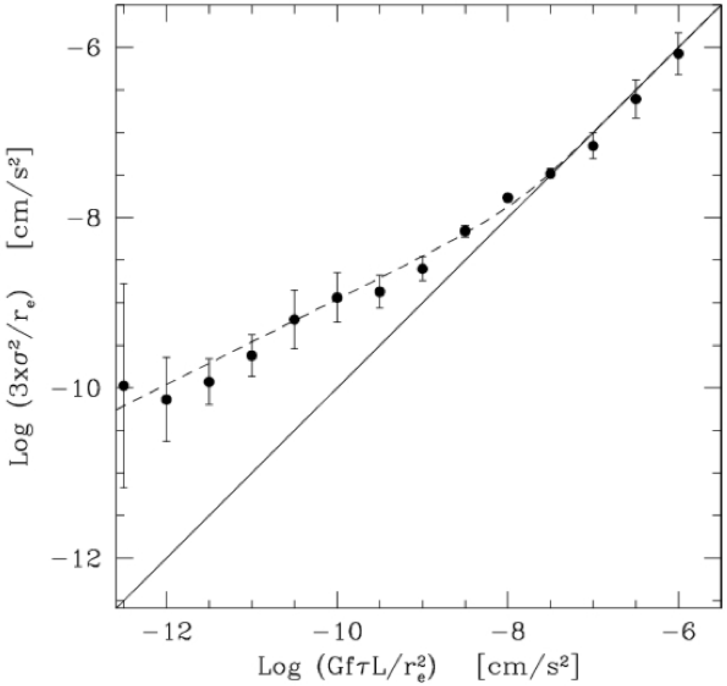
For $g_N \ll a_0$, $g/g_N \approx (g_N/a_0)^{-1/2}$

For $g_N \gg a_0$, $g/g_N \approx 1$



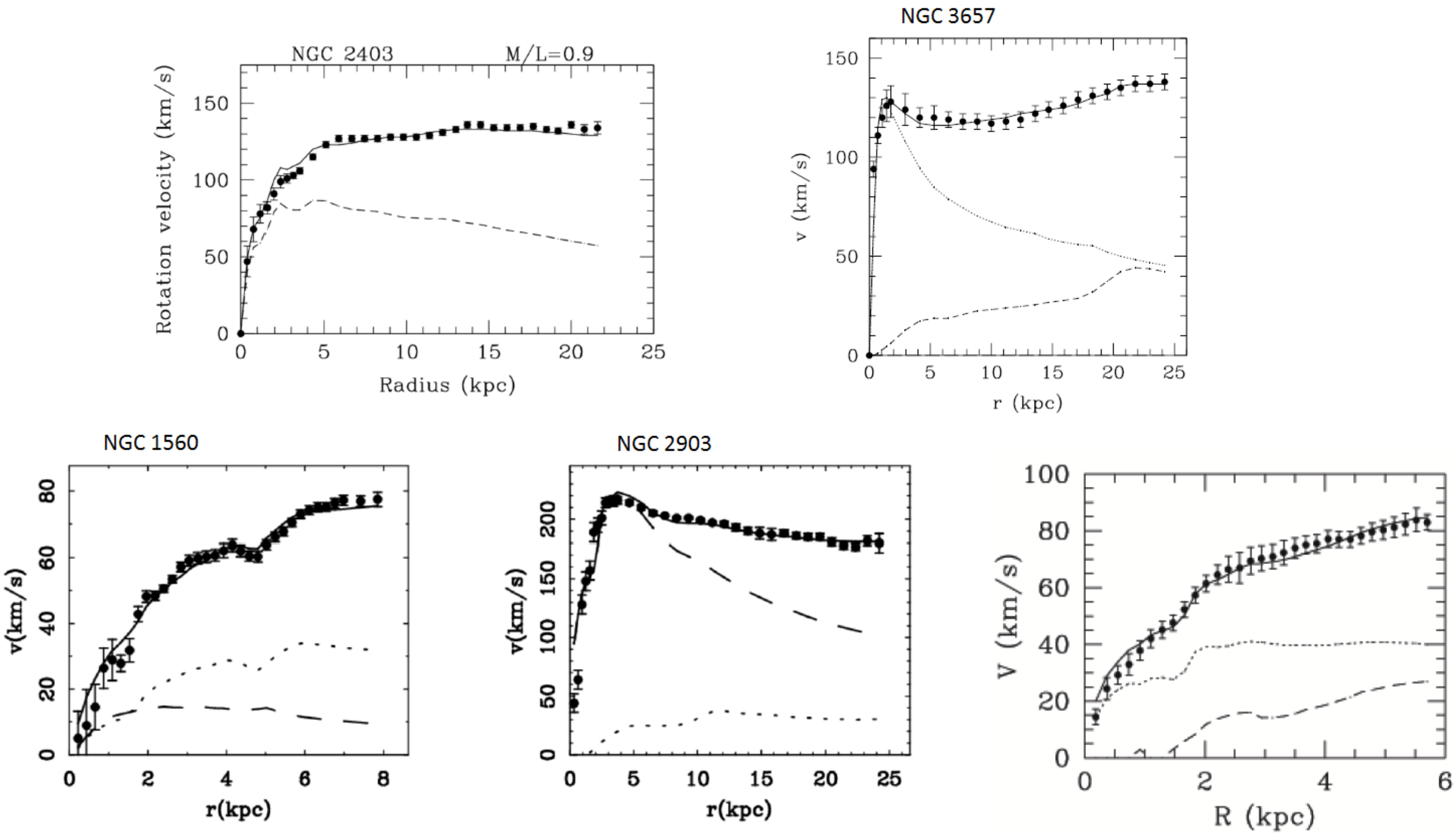
73 disc galaxies from McGaugh (2015).

Discrepancy-acceleration correlation for pressure-supported systems

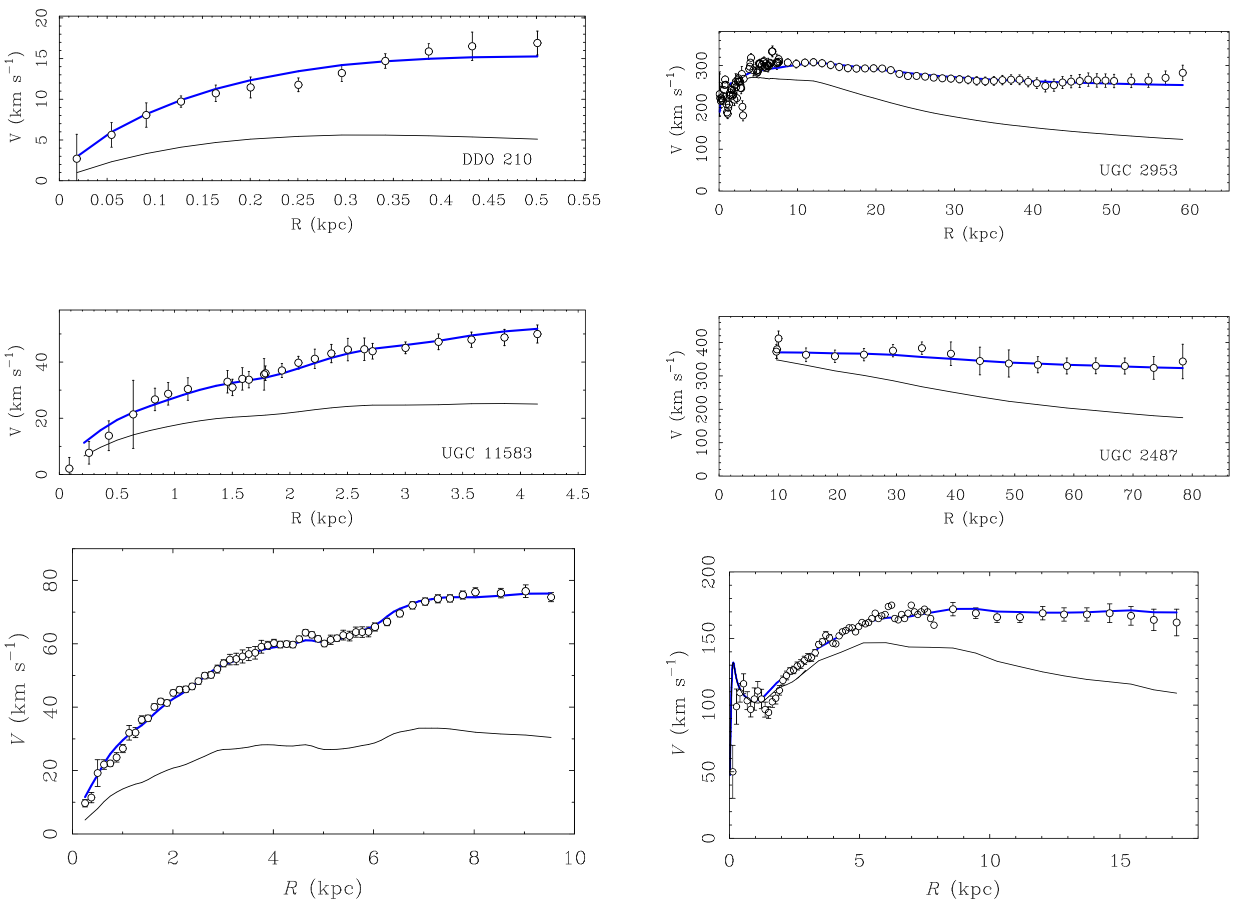


g vs. g_N, Scarpa (2006)

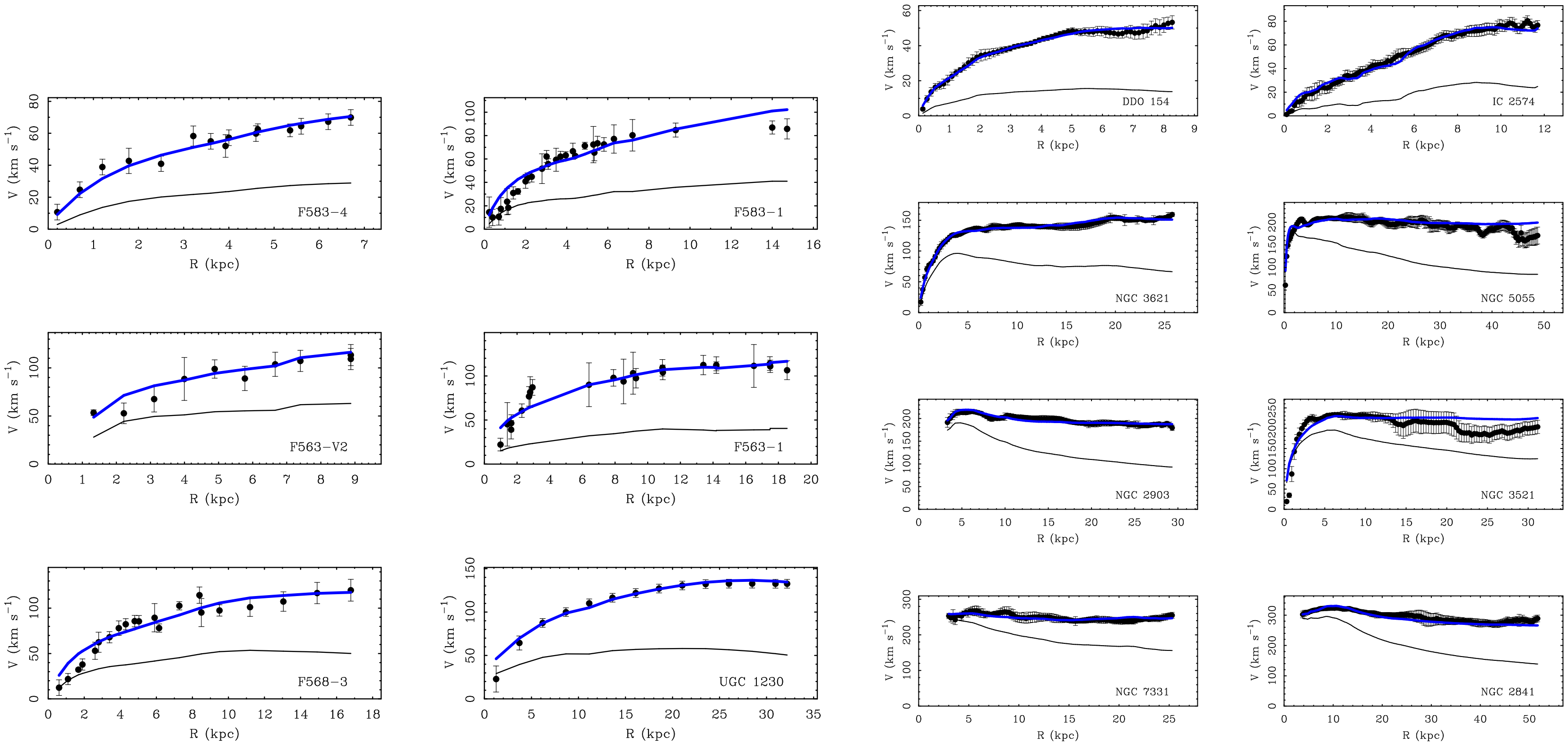
Rotation Curves of Disc Galaxies



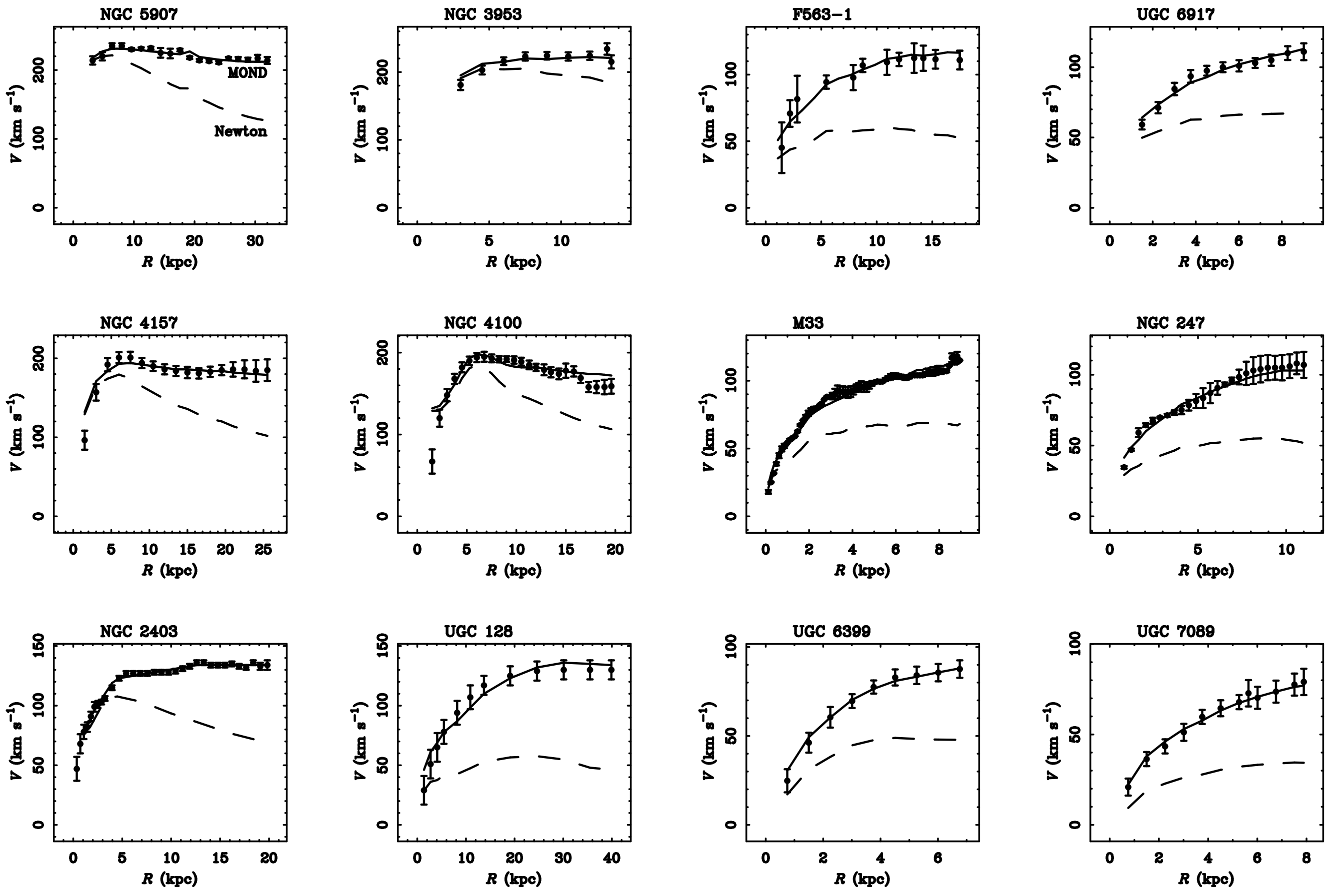
Sanders 2005 and Sanders and McGaugh 2002



Famaey and McGaugh (2012)

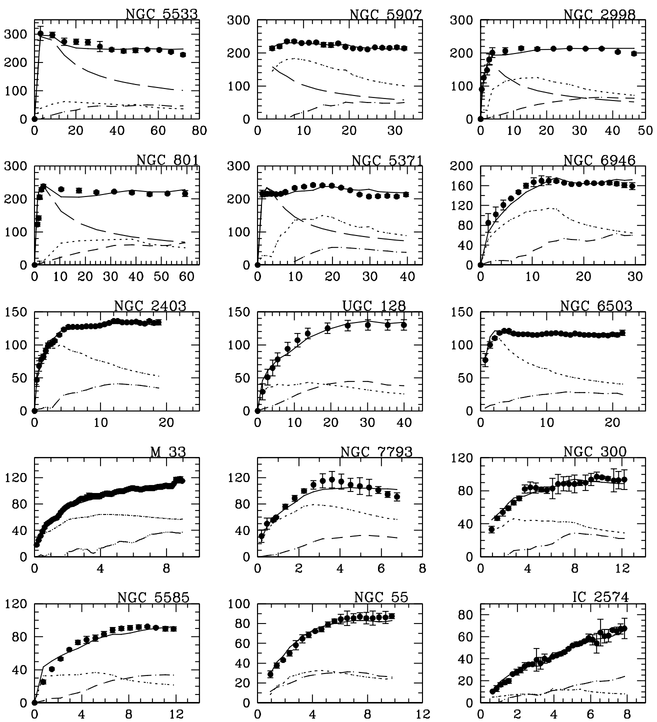


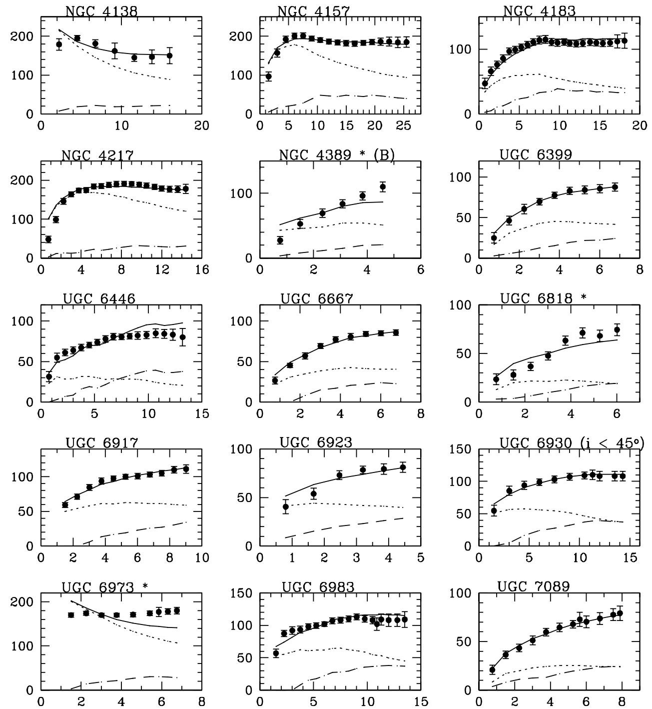
Famaey and McGaugh (2012)


NGC 5907
NGC 3953
F563-1
UGC 6917
NGC 4157
NGC 4100
M33
NGC 247
NGC 2403
UGC 128
UGC 6399
UGC 7089
MOND
Newton
V (km s^{-1})
R (kpc)

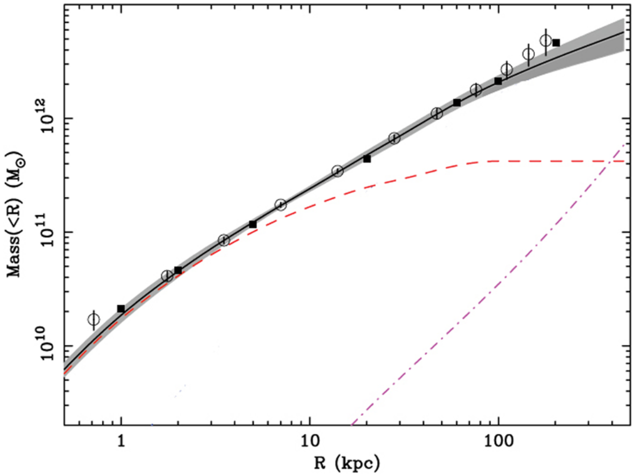
McGaugh

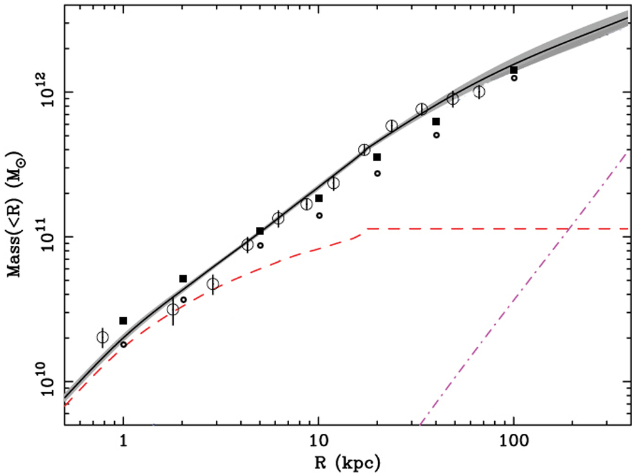
Sanders and McGaugh 2002



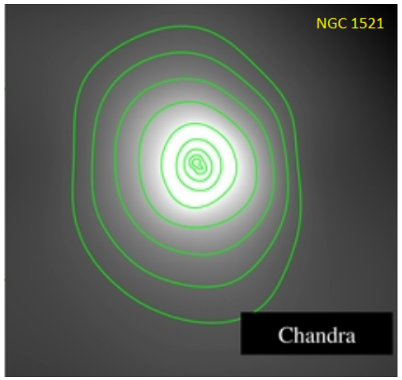


x-ray Ellipticals, tested over an acceleration range $\sim 10a_0 - 0.1a_0$

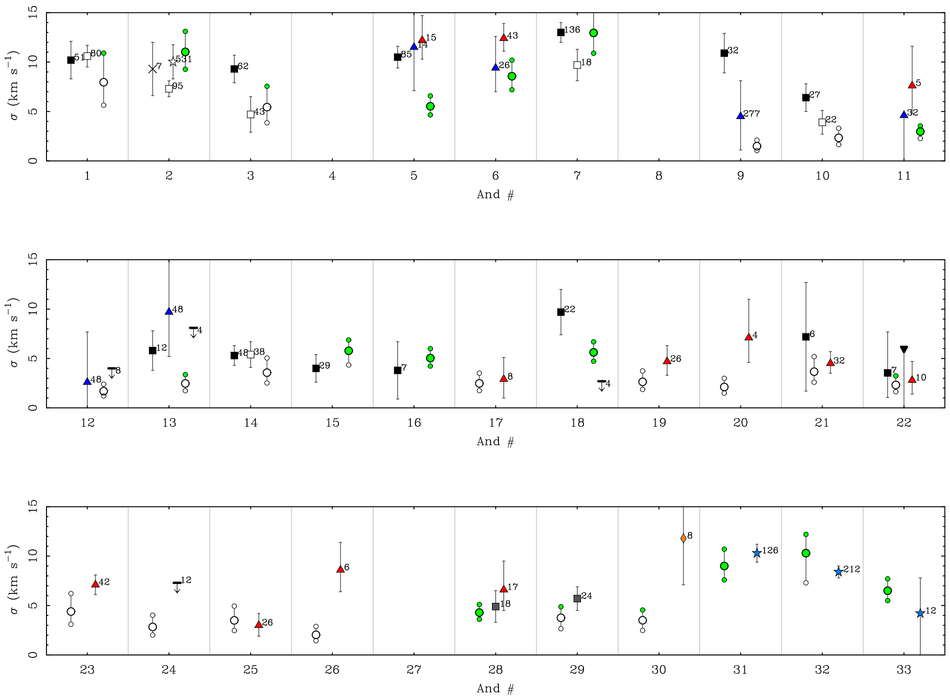




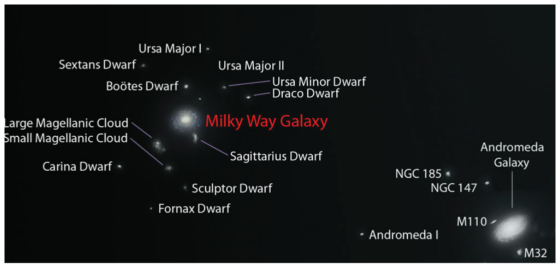
Baryon and dynamical masses from Humphrey et al. 2011, 2012. MOND predictions as squares and rings



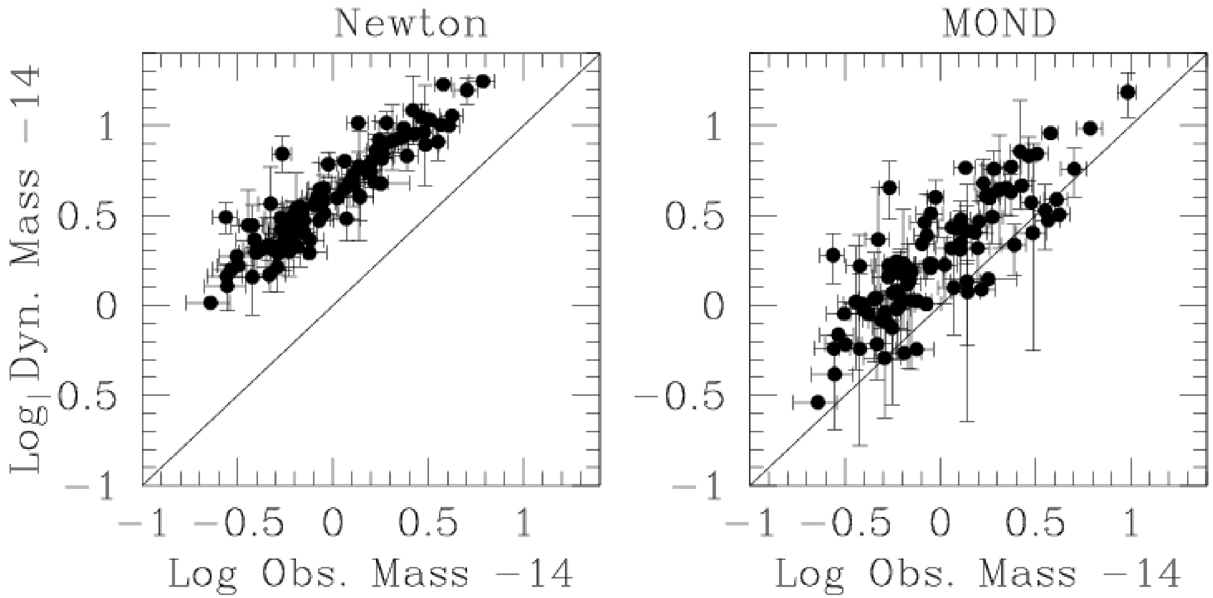
Andromeda satellites–internal dynamics



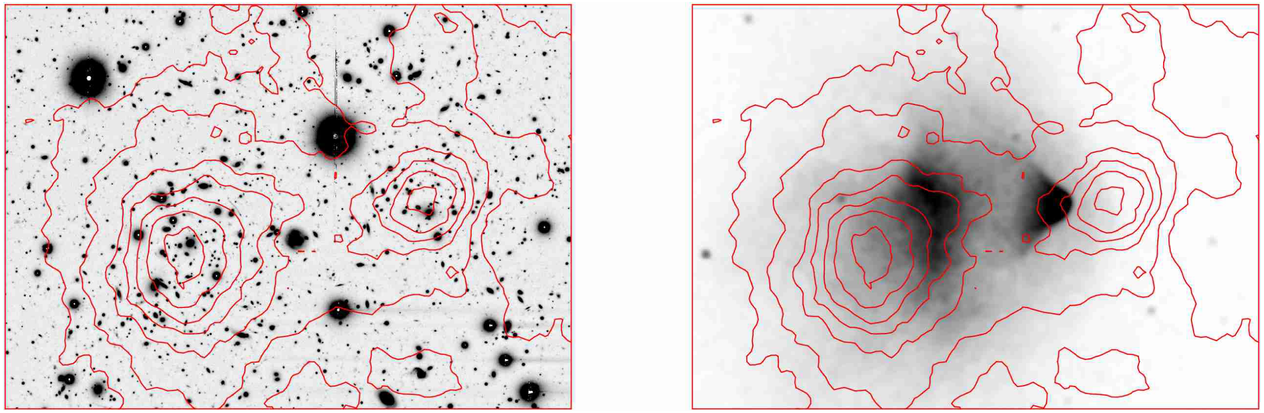
McGaugh and Milgrom 2013.



Galaxy Clusters



Sanders 1999

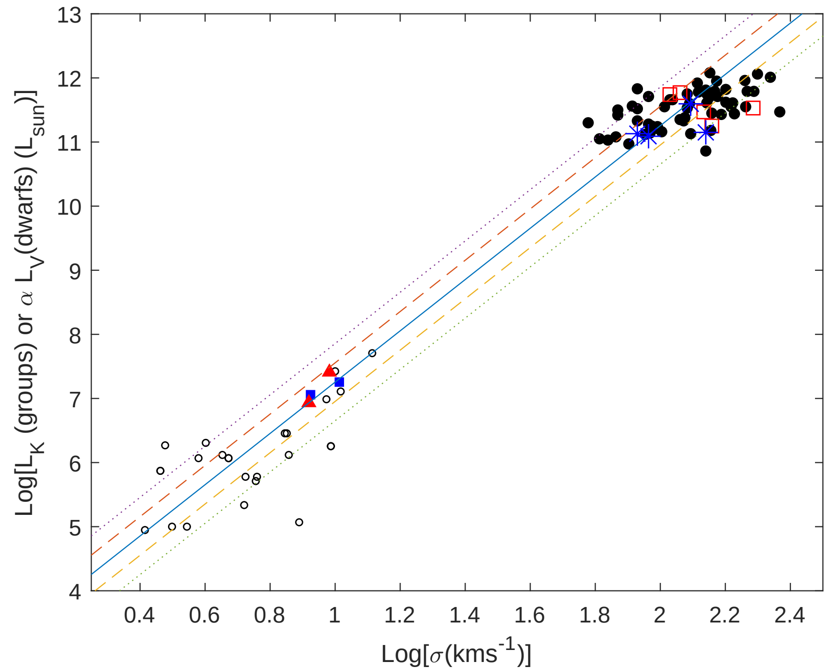


Clowe et al. 2006

Galaxy groups

General properties (in comparison with other systems): Mass, velocities, sizes, accelerations. Compare with clusters (not a question of scales).

$$MGa_0 = \frac{81}{4}\sigma^4$$



Some MOND-DM discriminants

- EFE is peculiar to MOND: Hints from andromeda dwarfs, Crater II, groups?
- Negative phantom matter
- Features on RCs
- Dynamical friction
- Disc stability in LSBs (DML)

Nonrelativistic theories

Nonlinear Poisson equation (AQUAL, Bekenstein & Milgrom 1984):

$$\vec{\nabla} \cdot [\mu(|\vec{\nabla}\phi|/a_0)\vec{\nabla}\phi] = 4\pi G\rho$$

The deep-MOND limit is conformally invariant

Quaslinear MOND (QUMOND, Milgrom 2010):

$$\Delta\phi_N = 4\pi G\rho, \qquad \Delta\phi = \vec{\nabla} \cdot [\nu(|\vec{\nabla}\phi_N|/a_0)\vec{\nabla}\phi_N]$$

Derivable from actions

Limits of relativistic theories (TeVeS, BIMOND, Einstein Aether)

Relativistic theories

- Tensor-Vector-Scalar Gravity (TeVeS–Bekenstein 2004, ideas from Sanders 1997) Gravity is described by $g_{\alpha\beta}$, $\mathcal{U}_\alpha$, ϕ: $\tilde{g}_{\alpha\beta} = e^{-2\phi}(g_{\alpha\beta} + \mathcal{U}_\alpha \mathcal{U}_\beta) - e^{2\phi}\mathcal{U}_\alpha \mathcal{U}_\beta$

- MOND adaptations of Aether theories (Zlosnik, Ferreira, & Starkman 2007, Hossenfelder 2017)

$$\mathcal{L}(A, g) = \frac{a_0^2}{16\pi G}\mathcal{F}(\mathcal{K}) + \lambda(A^\mu A_\mu + 1);$$

$$\mathcal{K} = a_0^{-2} A^\gamma{}_{;\alpha} A^\sigma{}_{;\beta}(c_1 g^{\alpha\beta} g_{\gamma\sigma} + c_2 \delta^\alpha_\gamma \delta^\beta_\sigma + c_3 \delta^\alpha_\sigma \delta^\beta_\gamma + c_4 A^\alpha A^\beta g_{\gamma\sigma}).$$

- Galileon k-mouflage MOND adaptation (Babichev, Deffayet, & Esposito-Farese 2011)

  Also a tensor-vector-scalar theory. Said to improve on TeVeS in various regards (e.g., small enough departures from GR in high-acceleration environments)

- Nonlocal metric MOND theories (Soussa & Woodard 2003; Deffayet, Esposito-Farese, & Woodard 2011, 2014) Pure metric, but highly nonlocal in that they involve $F(\Box)$.

- BIMOND (Bimetric MOND) (Milgrom 2009-2013)

$$I = -\frac{1}{16\pi G}\int [R + \hat{R} + \ell_M^{-2}\mathcal{M}(\ell_M^2 C^2)]dv + I_M + \hat{I}_M$$

- MOND from a specialized formulation of $f(R)$ theories (Bernal, Capozziello, Hidalgo, & Mendoza 2011, Barrientos & Mendoza 2016)

- Massive bi-gravity plus a polarizable medium (Blanchet & Heisenberg 2015)

“Microscopic” approaches

- Vacuum effects (Milgrom 1999)

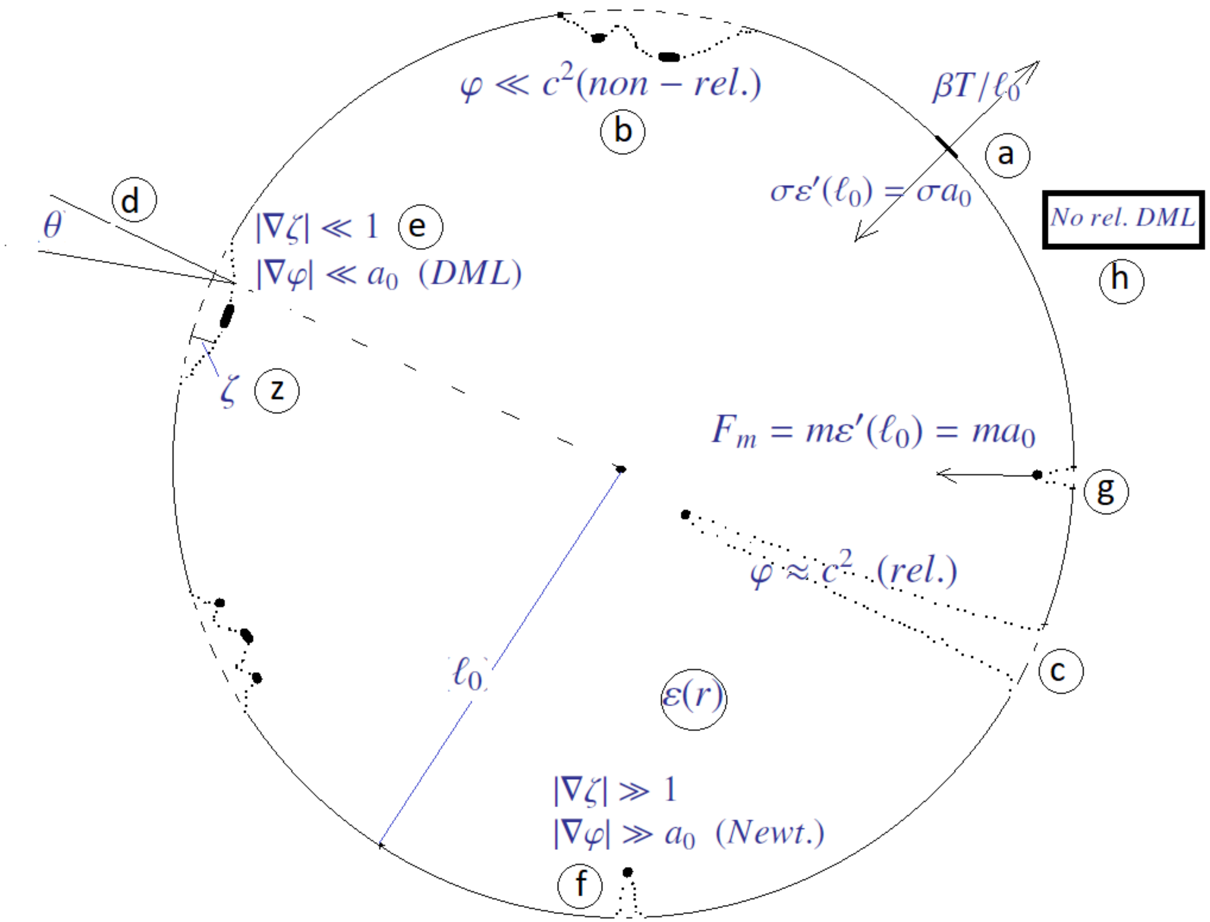
- Membranes with gravity=extra dimensions (Milgrom 2002, 2018)

- Omnipresent medium with MOND-like effects:
  - ▹ Polarized dark medium (Blanchet 2007, Blanchet & Le Tiec 2009, Blanchet & Heisenberg 2015)
  - ▹ Dark Fluid (Zhao 2008)
  - ▹ Novel baryon-DM interactions (Bruneton & al. 2008; Famaey, Khoury, & Penco 2018)
  - ▹ Superfluid (Khoury, Berezhiani & Khoury 2015)

- Entropic effect (Pikhitsa Ho & al. 2010, Li & Chang 2010, Klinkhamer & Kopp 2011, Verlinde 2017, others)

- Horava gravity (Romero & al. 2010, Sanders 2011, Blanchet & Marsat 2011)

MOND from Membrane



$\varphi \equiv \varepsilon \approx \varepsilon(\ell_0) + \varphi_0 + \varepsilon'(\ell_0)\zeta = a_0\zeta$ $\qquad tg(\theta) = |\vec{\nabla}\zeta| = |\vec{\nabla}\phi/a_0|$

$\varphi/c^2 = a_0\zeta/c^2 = \zeta/\ell_0 \qquad a_0 \equiv |\varepsilon'(\ell_0)| \qquad T/\sigma = \alpha c^2$

Dictionary: Geometry $\rightarrow$ Dynamics

- Membrane mean radius, $\ell_U \rightarrow$ observed CC $\Lambda^{-1/2}$

- Membrane density and tension (pressure) $\rightarrow$ (unobserved) big (vacuum) CC

- Departure from the 'sphere', $\zeta \rightarrow$ gravitational (MOND) potential $\phi \approx a_0 \zeta$

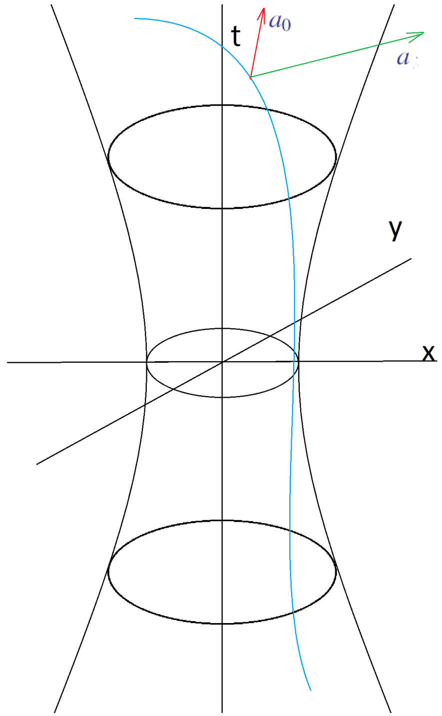
- $\zeta \ll \ell_U$ ($\phi \ll c^2$) $\rightarrow$ Newtonian gravity; $\zeta \not\ll \ell_U \rightarrow$ Relativistic gravity (NS, BH)

- Small membrane gradient ($\vec{\nabla}\zeta \ll 1$) $\rightarrow$ Deep MOND ($|\vec{\nabla}\phi| \ll a_0$); while $\vec{\nabla}\zeta \ll 1 \rightarrow$ Newtonian

de Sitter connection

Consequences : No deep-MOND black holes.

de Sitter generalization?



$$X^2 \equiv X^a \eta_{ab} X^b = \ell_\Lambda^2, \qquad X^a, \qquad a = 0, 1, ..., 4$$
$$n^a \eta_{ab} \ddot{X}^b = 1/\ell_\Lambda = a_\Lambda, \qquad a_5^2 = a^2 + a_\Lambda^2$$

Summary

- MOND is still under construction with new physics at $a \lesssim a_0 \sim cH_0 \sim c\Lambda^{1/2}$.

- It is anchored in symmetry.

- Several theoretical directions.

- It achieves a lot, and does it very well.

- Does not yet account for everything.

- Unlikely to be explained as some organizing principle for CDM.